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# GUIDANCE DOCUMENT
# SEISMIC CONSIDERATIONS
# HAZARDOUS WASTE MANAGEMENT FACILITIES

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This document is concerned with earthquakes as a threat to public safety and welfare in a significant portion of the United States.

The regulations prohibits hazardous waste management facilities from locating within 200 feet of a fault which has had displacement in Holocene Line (Approximately the Last 11,000 years). Such a fault is therefore referred to as a holocene fault within this document. These facilities required to comply with this regulation are to demonstrate that the facility is not within 200 feet of a holocene fault.

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SEISMIC CONSIDERATIONS

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## 1.0 INTRODUCTION

Earthquakes present a threat to public safety and welfare in a significant portion of the United States. Damage and loss of life in earthquakes occur as a result of ground shaking (ground motion), secondary effects of the shaking such as ground failure, and permanent surface displacement along faults (surface faulting). The final regulation addresses one of these hazards, surface fault displacement.

The regulation prohibits hazardous waste management facilities from locating within 200 feet of a fault which has had displacement in Holocene time (approximately the last 11,000 years). Such a fault is hereafter referred to as a Holocene fault within this document. Those facilities required to comply with this regulation are to demonstrate that the facility is not within 200 feet of a Holocene fault.

## 2.0 FINAL REGULATION - LOCATION STANDARDS

### 2.1 SEISMIC CONSIDERATIONS

Owners or operators of new facilities must demonstrate to the Regional Administrator that portions of new facilities where treatment, storage, or disposal of hazardous waste will be conducted are not location within 61 meters (200 feet) of a fault which has had displacement in Holocene time.

"Fault" means a fracture along which rocks on one side have been displaced with respect to those on the other side.

"Displacement" means the relative movement of any two sides of a fault measured in any direction.

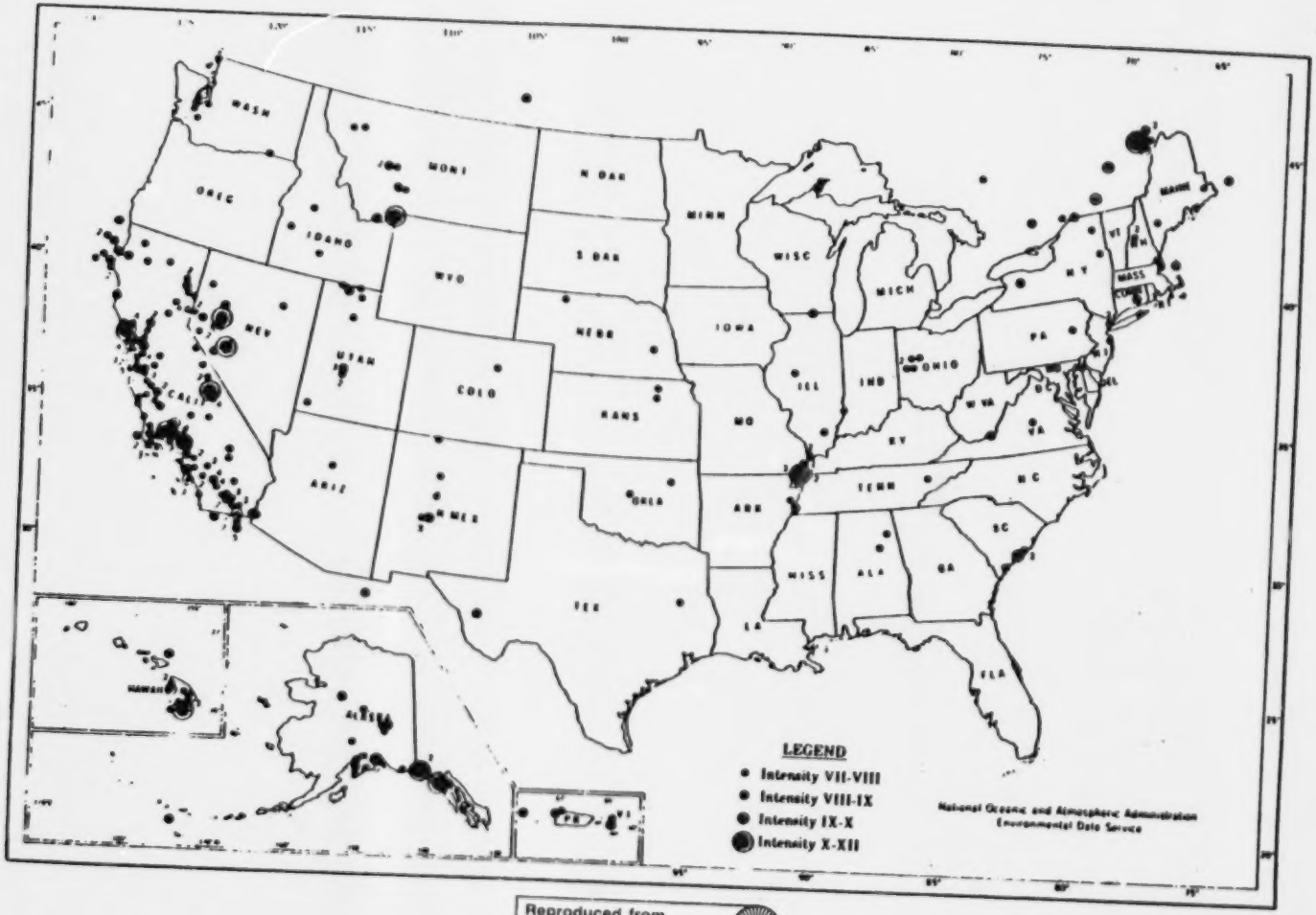
"Holocene" means that most recent epoch of the Quaternary period, extending from the end of the Pleistocene to the present.

## 2.2 NEED FOR THE REGULATION

### 2.2.1 Earthquakes and Fault Displacement

In some areas of the United States there is a recognized potential for damage associated with earthquakes. The location of historical damaging earthquakes in the United States are shown on Figure 1, and the potential for future earthquake damage is shown on Figure 2. A total of 39 states may be subject to moderate to severe earthquakes with a potential for damage to structures and loss of life (Applied Technology Council, 1978).

Earthquakes occur when the rock deep in the earth's crust is strained to the breaking point. The accumulated strain is suddenly released by displacement of the rock, generally along a pre-existing fault plane, and elastic vibrations radiate out in all directions from the point of rupture. In most cases the displacement along the fault occurs miles below the earth's surface and results in earthquakes of varying magnitude and intensity. These earthquakes can produce ground shaking which may (under certain conditions) result in secondary ground failure or damage to structures within the area influenced at the shaking. In still other cases the fault displacement may extend to the surface and near surface resulting in ground shaking, secondary ground failure, and surface fault displacement. Earthquakes and faults are discussed in more detail in Appendix A which should be read to obtain a common understanding.

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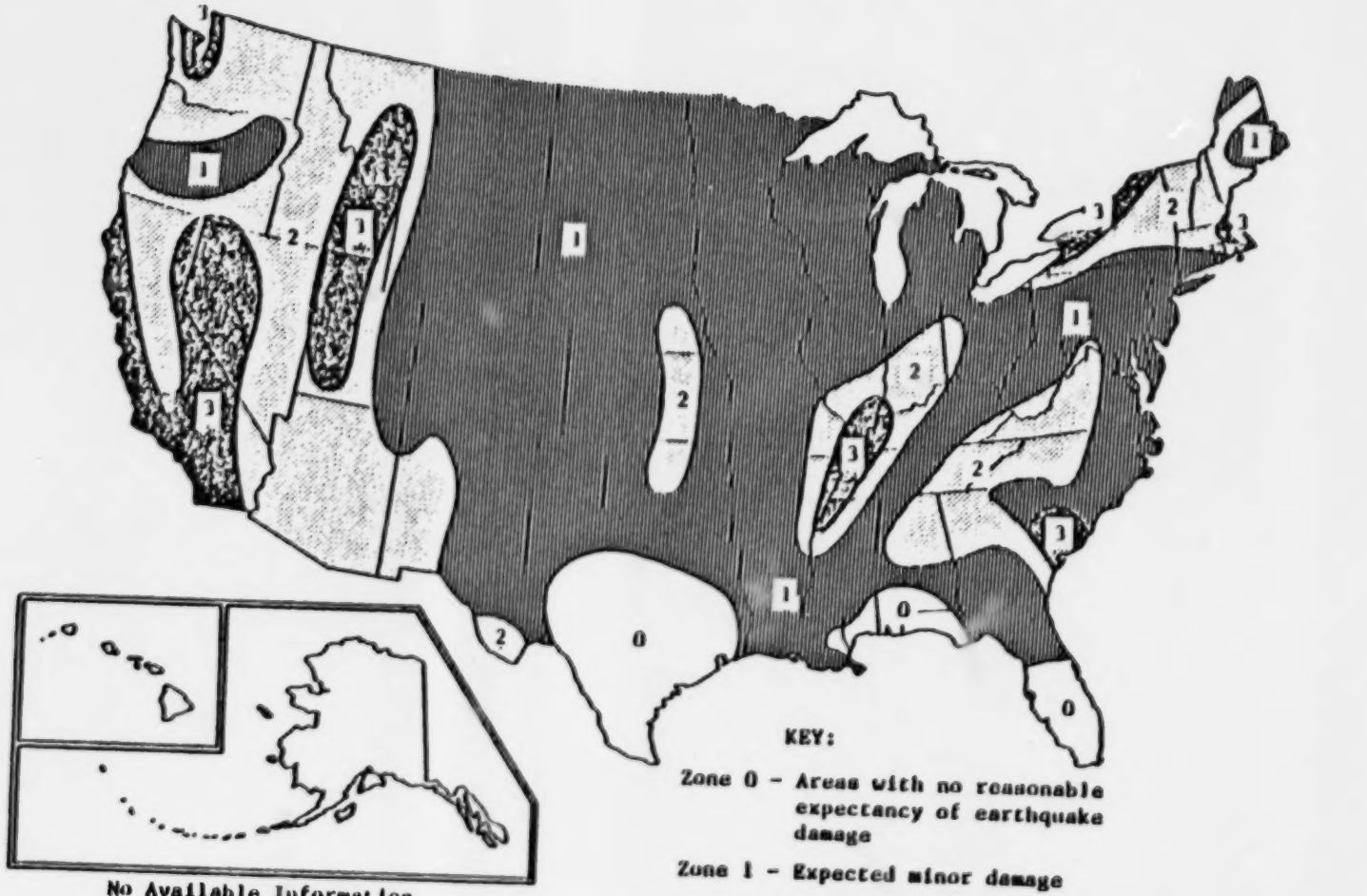
SOURCE: Coffman and Von Hake, 1973

**FIGURE 1**

**DAMAGING EARTHQUAKES IN THE UNITED STATES
FROM EARLIEST HISTORY THROUGH 1971**


No Available Information
KEY:
Zone 0 - Areas with no reasonable expectancy of earthquake damage
Zone 1 - Expected minor damage
Zone 2 - Expected moderate damage
Zone 3 - Where major destructive earthquakes may occur

SOURCE: Executive of the President, 1972

FIGURE 2

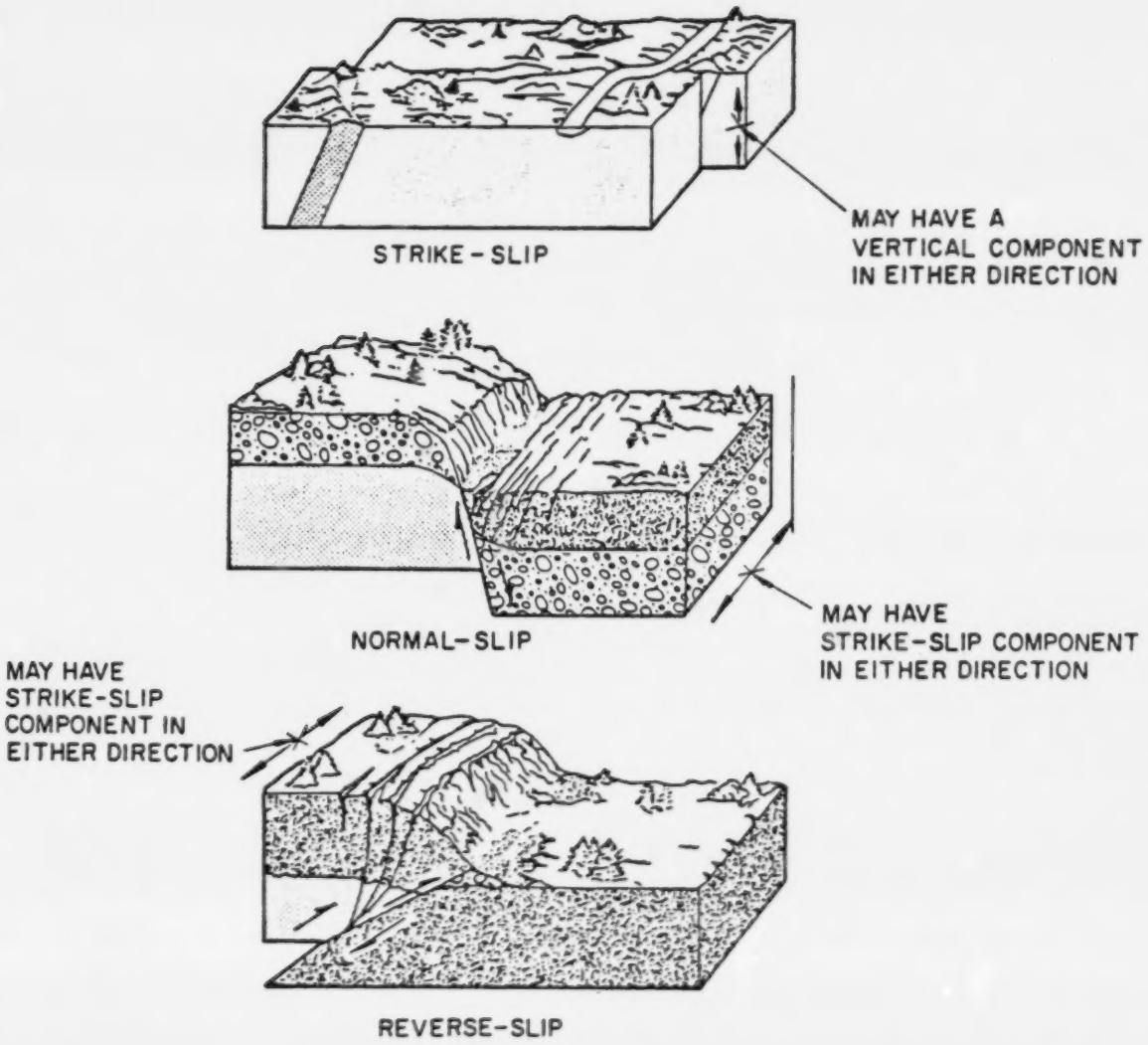
POTENTIAL FOR EARTHQUAKE DAMAGE IN UNITED STATES

In some parts of the world and the Eastern United States the fault displacement may be confined to the subsurface with no surface expression of the displacement. In other parts of the world and the Western United States the displacement generally continues the surface with fault displacement at or near the ground surface. Surface fault displacement is generally associated with three types of faults as shown on Figure 3 and discussed in Appendix B.

### 2.2.2 Surface Faulting

Surface faulting is displacement or distortion at or near the ground surface caused by displacement along a fault. For the period 1857-1976 surface faulting was reportedly associated with 87 worldwide earthquakes, including 28 earthquakes within the United States (Slemmons, 1977). The faulting as the movement or fracturing along fault is called had horizontal and vertical components of displacement and varied from a fraction of an inch to many feet. In the San Francisco earthquake of April 18, 1906, horizontal displacements along the San Andreas fault averaged from 8 to 15 feet and the faulting extended for a distance of mode than 200 miles along the fault. Structures located within the relatively narrow area subjected to surface fault displacement were damaged and sometimes destroyed. It is generally considered economically unfeasible and, in some cases, impossible to design a critical facility to resist significant fault displacement. For this reason many governmental agencies have adopted regulations prohibiting construction of certain structures adjacent to faults which are considered a potential location of surface faulting during the life of the structures (Slemmons, 1977).

Hazardous waste management facilities include containers, tanks, surface impoundments, waste piles, land treatment, land fills, incinerators, and structures for thermal, chemical,


STRIKE-SLIP
MAY HAVE A VERTICAL COMPONENT IN EITHER DIRECTION
NORMAL-SLIP
MAY HAVE STRIKE-SLIP COMPONENT IN EITHER DIRECTION
MAY HAVE STRIKE-SLIP COMPONENT IN EITHER DIRECTION
REVERSE-SLIP

SOURCE: Taylor and Cluff, 1977

**FIGURE 3**

**THREE TYPES OF FAULT DISPLACEMENT**

physical and biological treatment. These facilities contain structures similar to those which have been damaged during past historical earthquakes and episodes of surface faulting (U.S. Geological Survey, 1971; Murphy, 1973; and Earthquake Engineering Research Institute, 1979). Therefore, in order to protect human health and the environment there is the need to regulate the location of hazardous waste management facilities in areas subject to fault displacement. The primary concern of this regulation is to avoid faults which could be the location of surface faulting during the design life of waste management facility. Although many of the facilities contain rather innocuous types of wastes, some facilities may contain toxic wastes or acents that could be released to the air or to the local groundwater supplies in the event of fault displacement and damage to the structure.

## 3.0 DEFINITIONS

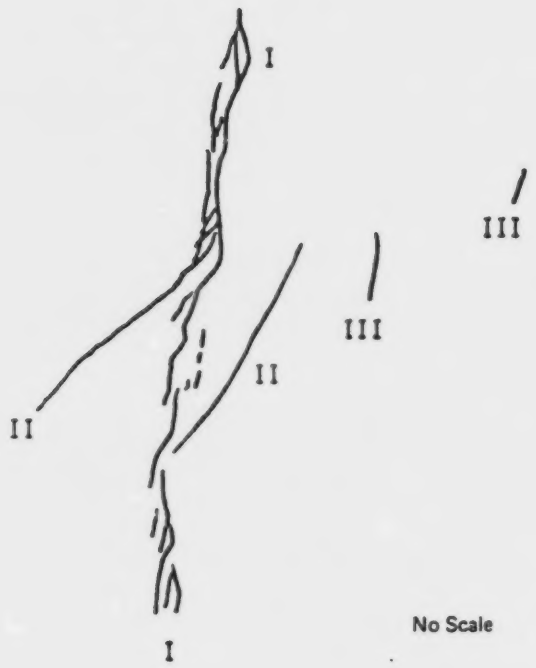
Appropriate Geological Investigation - A fault investigation directed at locating existing faults and then attempting to evaluate the recency of activity.

Branch Fault - A fault or fault trace that diverges from a main fault (Figure 4).

Displacement - The relative movement of any two sides of a fault measured in any direction.

Fault - A fracture along which rocks on one side have been displaced with respect to those on the other side.

Fault Trace - The line formed by the intersection of a fault and the ground surface or near surface materials. The representation of a fault as depicted on a map.




SOURCE: Bonilla, 1967

FIGURE 4

TYPES OF SURFACE FAULTING (I-PRIMARY OR MAIN, II-BRANCH, AND III-SECONDARY)

Fault Zone - A zone of related faults which commonly are braided and subparallel, but may be branching and divergent.

Geologist - A person engaged in the practice of geology.

Holocene - The most recent epoch of the Quaternary period, extending from the end of the Pleistocene to the present. A geological epoch which represents about the last 11,000 years (in some parts of the United States the upper limits of the Holocene may range from 10,000 to 15,000 years ago). This definition also includes recent historic time of about 200 years.

Main Fault - The fault with the greatest displacement, length, and continunity. Sometimes referred to as first, original, primary or principal fault trace (Figure 4).

Qualified Geologist - A qualified geologist shall have all of the following qualifications:

Responsible Position - A position whereby a person having independent control and direction of a geological project exercises the initiative, skill and independent judgment in the investigation and intrepretation of geological features, or the supervision of such projects.

Secondary Fault - Fault completely separate spatially from the main fault. The displacement is generally the same type as the main fault, but the amount of displacement is less (Figure 4).

Surface Faulting - Displacement or distortion at or near the ground surface caused by displacement along a fault.

## 4.0 MEANING OF REGULATION

### 4.1 BASIC PREMISE

The regulation states that hazardous waste management facilities are not to be located within 61 meter (200 feet) of a fault which has had displacement in Holocene time, about the last 11,000 years. The basic premise applied to identifying and locating faults which may be significant to man-made structures is that the type, amount, and location of fault displacement in the future will be similar to that which has occurred in the Recent geologic past. This premise has been substantiated by the results of studies which demonstrate that surface fault rupture typically is confined to a relatively narrow zone along pre-existing fault trace (Cluff, 1968;

Slemmons, 1968; Rodgers, 1973; Swan, Schwartz, and Cluff, 1980; and Wallace, 1968).

In almost all known instances of historic faulting, surface displacements have occurred along a pre-existing fault that had previous displacement in Holocene time and could have been recognized by geologists prior to the earthquake as a potential source of future activity (Cluff, Slemmons and Waggoner, 1970). Holocene deposits and active faulting are discussed in Appendix C. The geologic and historic record of fault activity shows that it is very likely that the displacement on a given fault will occur on or near the most recently active fault trace (Sherard, Cluff and Allen, 1974; Wallace, 1968). For an engineering project or structure located across or in the vicinity of a fault, the primary consideration is the recurrent movement on that fault within a time period which is significant to that project or structure. The recurrent movement on a fault with Holocene displacement is short enough to be significant to hazardous waste management facilities. Therefore, these facilities should be located to avoid the potential effects of displacement along Holocene faults.

## 4.2 CONSEQUENCE OF NON-COMPLIANCE

The potential effects of locating structures across a fault which has had Holocene displacement are horizontal and vertical fault displacement (with possible deformation) on the order of a few inches or feet to as much as 20 feet or more. The actual amount of displacement will depend upon the geometry and characteristics of each individual fault. These displacements could result in values which would exceed the design limits of waste facility structures and failure could result with a hazard to life and the environment.

Structures located across a fault at the time of surface faulting will be subjected to fault displacement. The amount and type of displacement and deformation (horizontal or vertical) will depend upon the type of fault (strike-slip, normal-slip, or reverse-slip) and displacement characterizatics (few inches or feet to as much as 20 feet or more). At the present time it is generally not practical to design critical structures to withstand serious damage under the stress of surface fault rupture.

Earthquakes and surface faulting occurs without advanced warning. Therefore, structures which are not designed to accomodate the displacement could be damaged. The consequence of damage or failure would depend upon the design of each structure or facility and the type of hazardous waste. The failure could be of no consequence or it could be a potential hazard to life and environment. Each facility may be unique based on the design, contents, and mitigating measures.

Earthen structures with solid waste such as land fills, embankments (surface impoundments), and waste piles would probably be less susceptible to failure than earthen structures with liquid waste. Based on experience with dams (Sherard, Cluff and Allen, 1974) earthen structures could probably be designed to be less susceptible to damage from surface faulting than could tanks, incinerators, or treatment facilities.

Non-compliance with this regulation could result in placement of a facility across a Holocene fault which has a high probability of displacement within the life of the facility. Such displacement could result in life loss, damage to the environment, or both.

## 5.0 COMPLIANCE

### 5.1 APPROACH BEING USED

Active portions of Hazardous Waste Management facility are to be located 61 meters (200 feet) beyond any fault with Holocene displacement. Therefore, the consideration is not the width of past surface faulting but that the facility or structures is located 61 meters (200 feet) from any fault having evidence of Holocene displacement. Based on the available information and the approach to be used, it appears that any facility sited on the basis of this regulation would be outside the zone of future faulting. Considering the same type of available information, the California Division of Mines and Geology (1980) specified that structure for human occupancy should be located at least 50 feet from a fault trace which had Holocene fault displacement, and the Public Utilities Commission of the State of California (1979) specified that for liquified natural gas facilities the actual set-back distance from a fault (which has had fault displacement in the last 100,000 to 140,000 years) will be established after completion of a detailed site study and that in no case may a LNG Tank be sited within 100 feet of such a fault.

There is need for site specific applications of the set-back distance. The real question is the risk that the facility is to be subjected to and this can better be determined once the type of facility is identified and appropriate geological studies have been conducted to; identify faults and their location with respect to the site, the age of faulting, evidence of past faulting and deformation, and subsurface conditions at the site. However, based on review of historical data, observation of faults and review of trenches across faults the approach and the use of a 61 meter (200 foot) set-back distance appears to be reasonable. Site specific

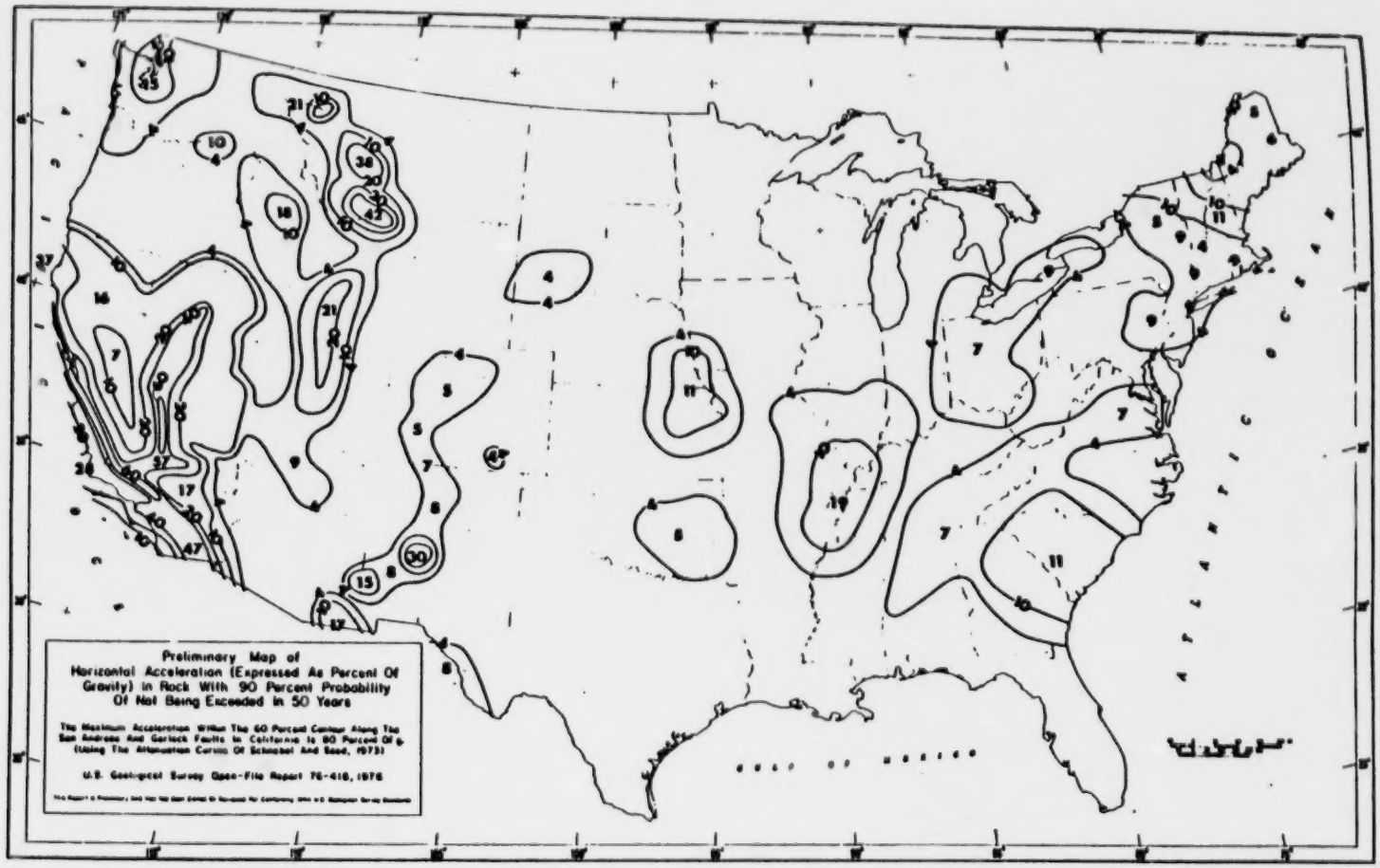
applications can be made to this set-back distance once the type of facilities have been identified and site specific data is available as to the local geologic conditions.

## 5.2 DETERMINE NEED FOR COMPLIANCE

Areas of the United States which have been the source of historical earthquakes and faulting in Holocene time are the areas most likely to contain Holocene faults. Seventy-one (71) seismic source zones have been identified by Algermissen and Perkins (1976). The source zones were used to construct a preliminary seismic risk map of horizontal acceleration in rock with 90 percent probability of not being exceeded in 50 years as shown on Figure 5.

A map by Howard and others (1978) shows "Young Faults in the United States as a Guide to Possible Fault Activity." All of the Holocene faults are shown in the western United States with the exception of an area around New Madrid, Missouri. No Holocene faults have been identified in the eastern United States. This may be due to a lack of young Holocene deposits to indicate displacements, a lack of site investigation to locate faults, or different tectonic condition with fault displacements confined to the subsurface. With continuing mapping by the United States Geological Survey and state surveys additional data will become available for the eastern Unites States. The areas of mapped Holocene faults occur within the zones identified in the Algermissen and Perkins map (Figure 5).

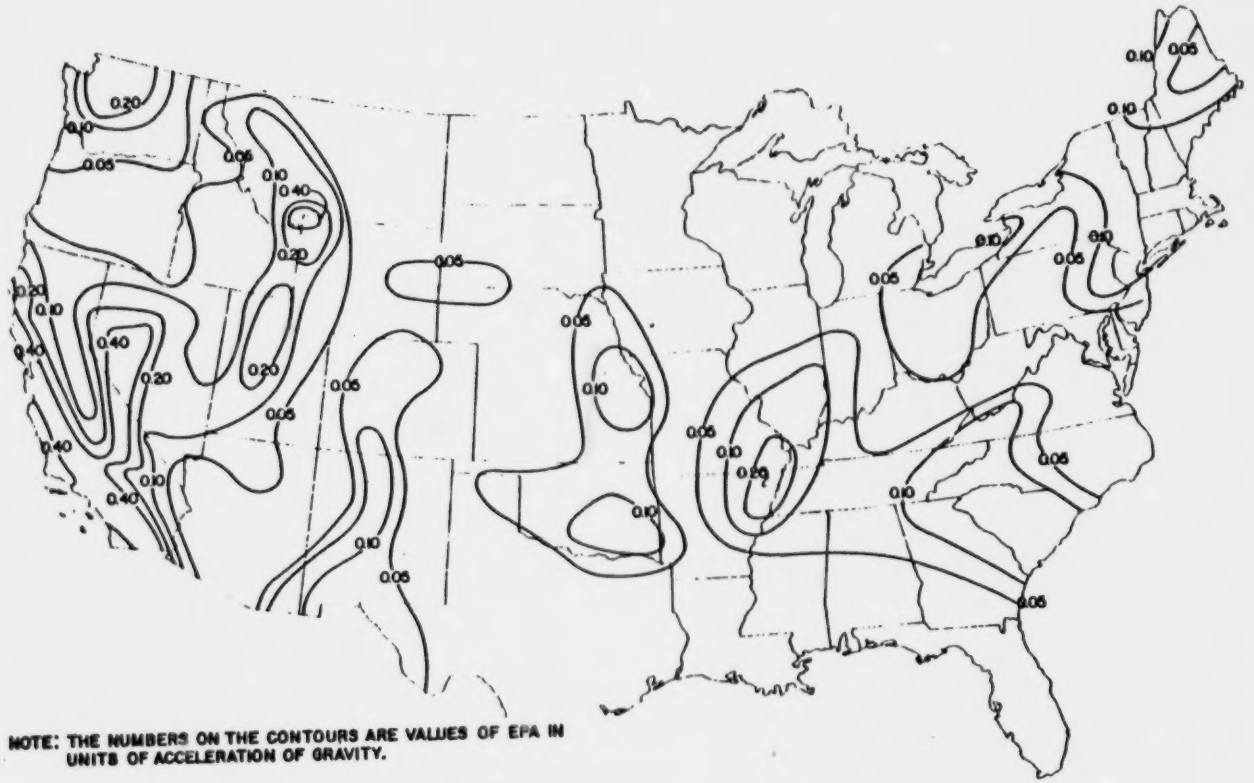
The seismic risk map (Figure 5) of Algermissen and Perkins (1976) has been modified by the Applied Technology Council (1978) to show contour maps for Effective Peak Acceleration as shown on Figure 6 and 7. The damaging historic earthquakes of the United States (Figure 1), and faults with reported Holocene


Preliminary Map of
Horizontal Acceleration (Expressed As Percent Of
Gravity) In Rock With 90 Percent Probability
Of Not Being Exceeded In 50 Years

SOURCE: Algermissen and Perkins, 1976

FIGURE 5

SEISMIC RISK MAP OF HORIZONTAL ACCELERATION IN ROCK
WITH 90 PERCENT PROBABILITY OF NOT BEING EXCEEDED
IN 50 YEARS

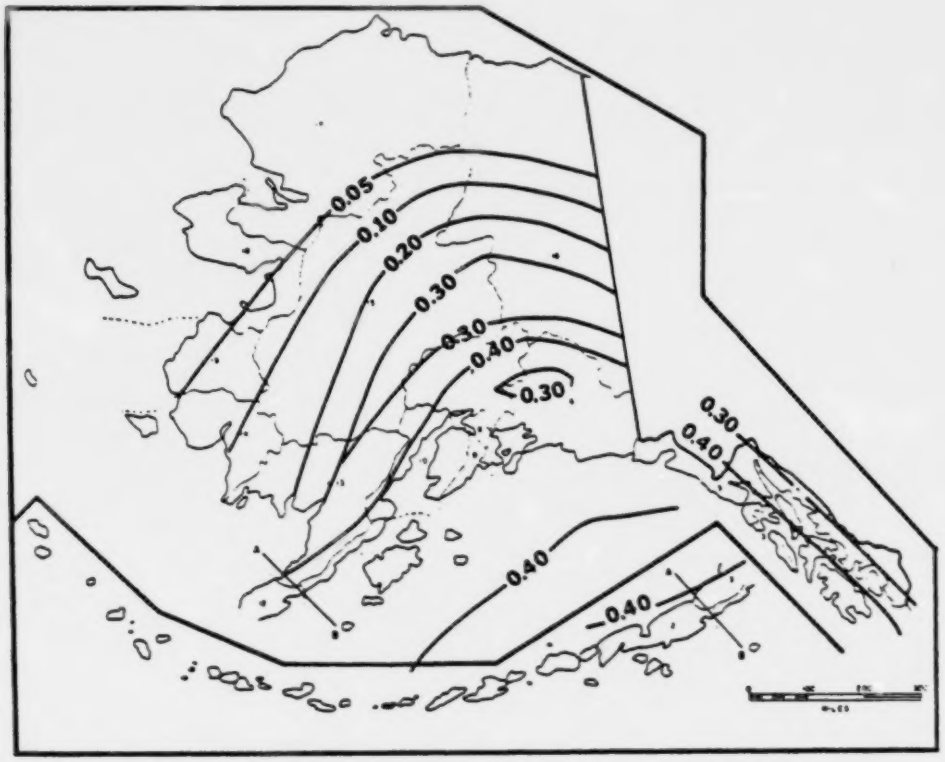



NOTE: THE NUMBERS ON THE CONTOURS ARE VALUES OF EPA IN UNITS OF ACCELERATION OF GRAVITY.

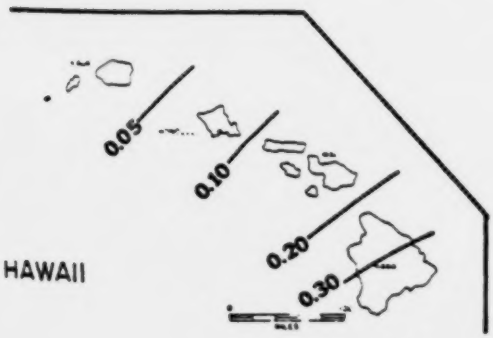
SOURCE: Applied Technology Council, 1978

**FIGURE 6**

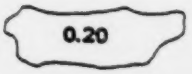
**CONTOUR MAP FOR EFFECTIVE PEAK ACCELERATION (CONTINENTAL UNITED STATES)**




ALASKA




HAWAII




PUERTO RICO

SOURCE: Applied Technology Council, 1978

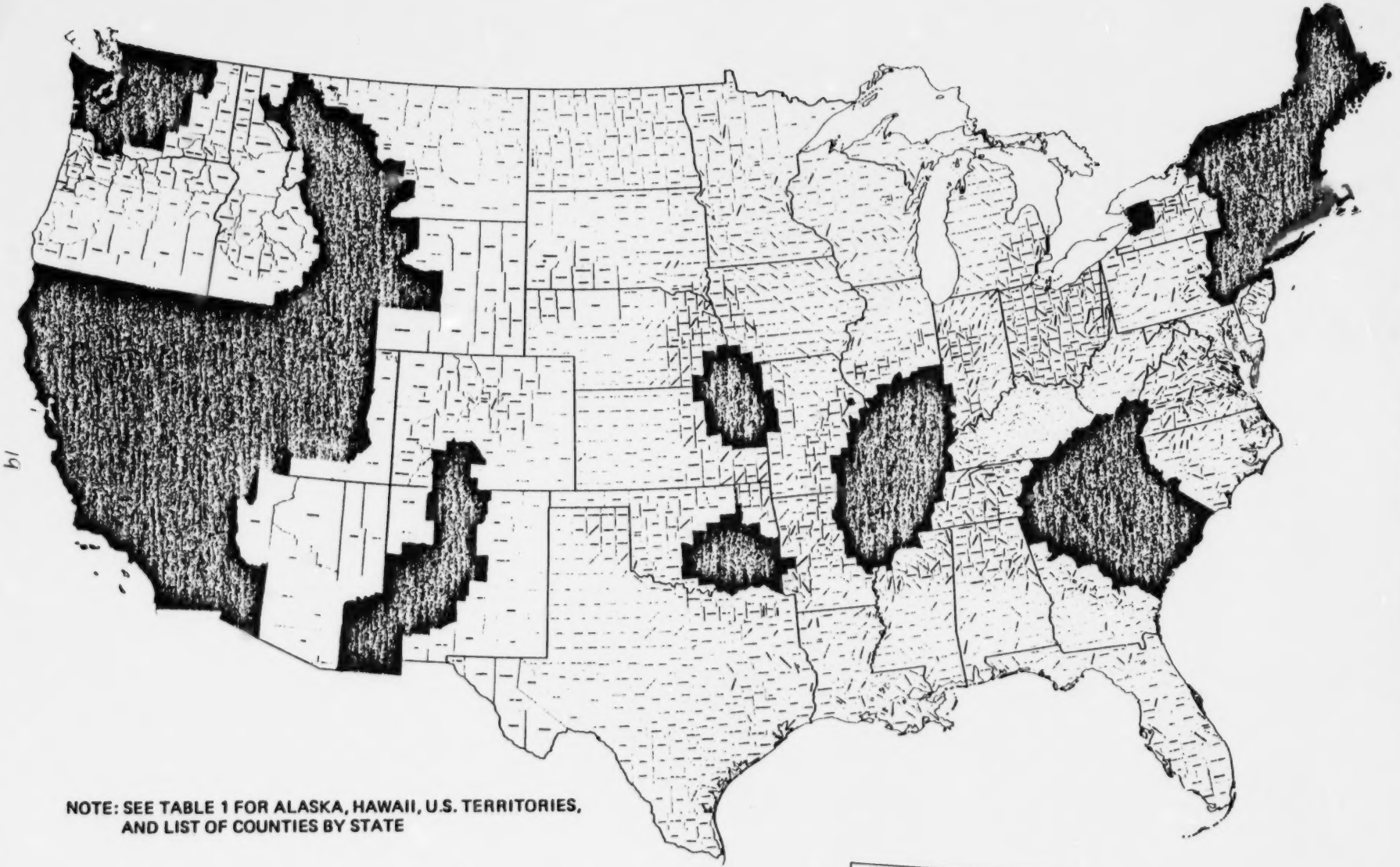
FIGURE 7

CONTOUR MAP FOR EFECTIVE PEAK ACCELERATION
(ALASKA, HAWAII, AND PUERTO RICO)

fault displacement (Howard, 1978) are within the 0.10 contour line (horizontal acceleration expressed as a function of gravity) on Figures 6 and 7. Based on the work by Howard and others (1978) and a review of other available data it appears that the areas of the United States most likely to be influenced by earthquakes with associated surface faulting are within the .10 contour line of Figures 6 and 7. These figures were modified by the Applied Technology Council (1978) to show the effective peak acceleration along county lines rather than along contour lines (Figure 1-1 of that report). Figure 8 delineates the areas of the United States within the .10 contour lines of Figures 6 and 7 (based on Figure 1-1 of the Applied Technology Council, 1978). Areas of the United States requiring compliance with the standard are shown on Figure 8 and listed on Table 1 by States and territories.

## 5.3 DEMONSTRATION OF COMPLIANCE

Owner or operators of new facilities must demonstrate to the Regional Administrator that portions of new facilities where treatment, storage, or disposal of hazardous waste will be conducted are not located within 61 meters (200 feet) of a fault which has had displacement in Holocene time. New facilities proposed within the governmental units (counties, election districts, or islands) shown on Figure 8 and listed in Table I are required to demonstrate compliance and conduct an appropriate geological study by a qualified geologist. The appropriate geological study will be described in the following section and a qualified geologist is described under definitions.



NOTE: SEE TABLE 1 FOR ALASKA, HAWAII, U.S. TERRITORIES, AND LIST OF COUNTIES BY STATE

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**FIGURE 8**

**AREAS OF THE UNITED STATES REQUIRING COMPLIANCE WITH THE STANDARD**

## 5.4 GUIDELINES FOR APPROPRIATE GEOLOGICAL STUDY

The purpose of the study is to document that active portions of the proposed facility are not located within 200 feet of a fault which has had displacement in Holocene time. The documentation may include, but not be limited to, review of existing geological data, interpretation of aerial photographs, aerial reconnaissance, ground reconnaissance, geological mapping, and subsurface exploration (trenching). The documentation shall be appropriate for the site and shall be of such quality as is acceptable to qualified geologist experienced in identifying and evaluating the activity of faults. The flow chart for the appropriate geological study is shown on Figure 9. Because site conditions will vary due to type and activity of faults, geological structures of the area, availability of geological data, and ground cover, two alternative study approaches are available to the applicant; a regional study and a site specific study.

The following sections discuss the methods and tools for conducting geological investigations, flow diagram for conducting a regional study, flow diagram for site specific study, basis for distances used in appropriate geologic study, and reporting.

### 5.4.1 Methods and Tools of Geologic Investigations

The methods and tools for conducting geological investigations include, but are not limited to review of published data, aerial reconnaissance, interpretation of aerial photographs, ground reconnaissance, and subsurface investigations.

5.4.1.1 Review of Existing Data - The review of existing data is directed towards obtaining information on the geology, regional faults and geological structures, and historical

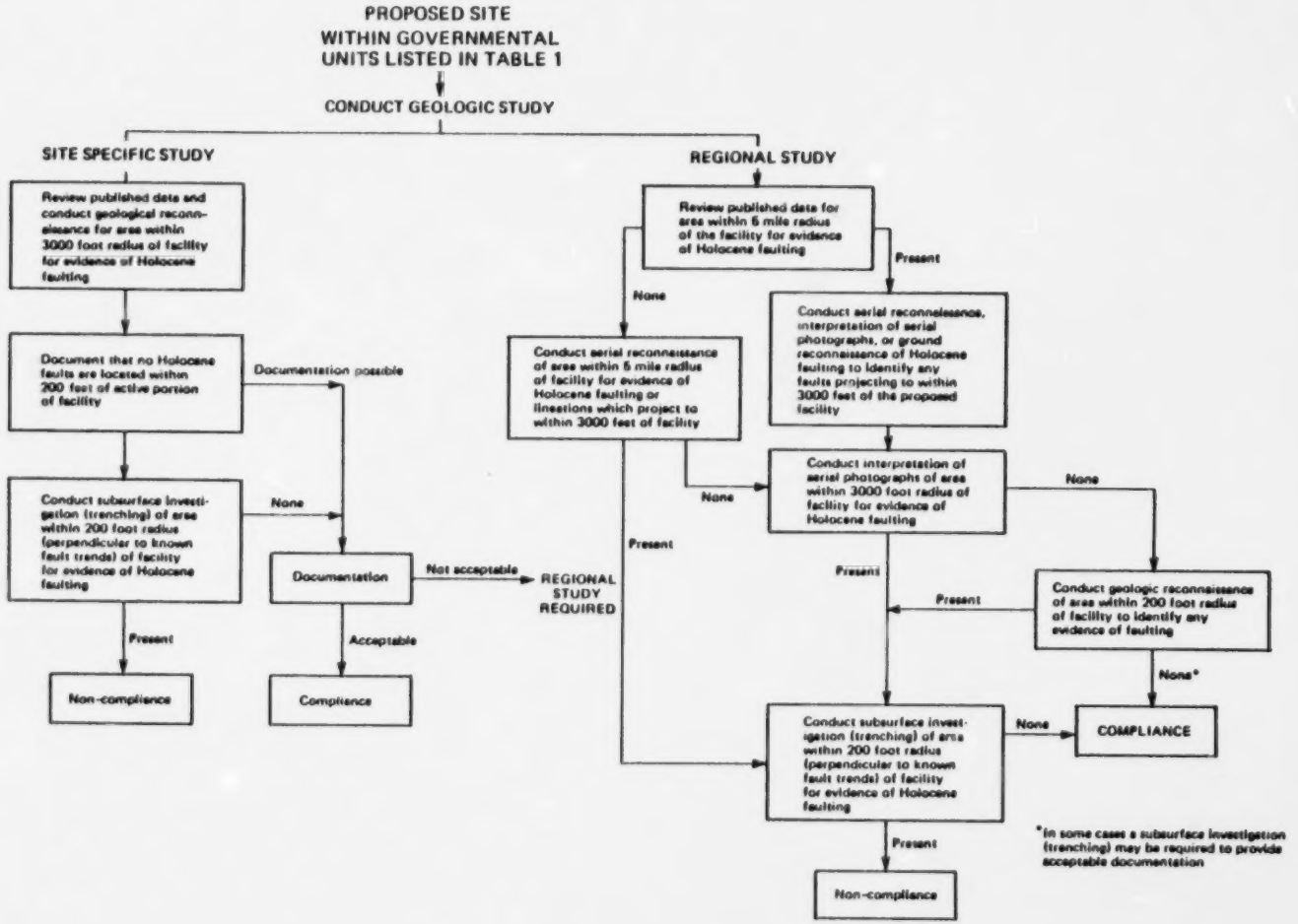
PROPOSED SITE
WITHIN GOVERNMENTAL
UNITS LISTED IN TABLE 1
CONDUCT GEOLOGIC STUDY
SITE SPECIFIC STUDY
REGIONAL STUDY
Review published data and conduct geological reconnaissance for area within 3000 foot radius of facility for evidence of Holocene faulting
Document that no Holocene faults are located within 200 feet of active portion of facility
Documentation possible
Conduct subsurface investigation (trenching) of area within 200 foot radius (perpendicular to known fault trends) of facility for evidence of Holocene faulting
None
Documentation
Not acceptable
REGIONAL STUDY REQUIRED
Present
Acceptable
Non-compliance
Compliance
Review published data for area within 5 mile radius of the facility for evidence of Holocene faulting
Present
None
Conduct aerial reconnaissance of area within 5 mile radius of facility for evidence of Holocene faulting or lineations which project to within 3000 feet of facility
Conduct aerial reconnaissance, interpretation of aerial photographs, or ground reconnaissance of Holocene faulting to identify any faults projecting to within 3000 feet of the proposed facility
None
Conduct interpretation of aerial photographs of area within 3000 foot radius of facility for evidence of Holocene faulting
None
Present
Present
Present
Conduct geologic reconnaissance of area within 200 foot radius of facility to identify any evidence of faulting
None*
Conduct subsurface investigation (trenching) of area within 200 foot radius (perpendicular to known fault trends) of facility for evidence of Holocene faulting
None
COMPLIANCE
Present
Non-compliance
*In some cases a subsurface investigation (trenching) may be required to provide acceptable documentation

FIGURE 9

APPROPRIATE GEOLOGIC STUDY

earthquakes to identify any published Holocene faults, through-going structural trends that may be related to faulting, concentrations of earthquake activity, and any historical accounts of major earthquakes and surface effects in the project area. In some cases there may be published information on the location and activity of faults near the site. More commonly, the geological information must be reviewed for a larger area and then brought into the site by some of the specific geological investigation methods discussed below.

The United States Geological Survey and the Geological Survey of the individual states are good sources of information concerning geology, faults, and historical earthquakes. Other sources include soil conservation service, local colleges and universities, county and city building departments or public works departments, and consulting geologists.

5.4.1.2 Aerial Reconnaissance - Aerial reconnaissance by an experienced observer can identify geomorphic fault features that could not be readily identified on the ground. Faults may appear as lineations or an alignment of features resulting from various physical conditions created by faulting, such as disruption of the normal ground surface along the lines of previous fault breaks, different soils on opposite sides, different rock types, different vegetation, and displaced topographic features. These features include scarps, offset drainage channels, saddles, sag ponds, ponded alluvium, closed depressions, displaced structure, shutter ridges or parallel ridges.

Aerial reconnaissance is best done in a high winged aircraft and when the visability is good. Early morning or late afternoon flights are generally better than midday flights because shadows enhance subdued ground-surface irregularities commonly observed along fault zones. The flight lines should

consist of two different orientations; one perpendicular to the geologic structures and the other one parallel to the geologic structures. In most cases it is best to have two observers, one on each side of the aircraft, in order to take advantage of the difference in lighting conditions.

5.4.1.3 Interpretation of Aerial Photographs - Studies of aerial photographs and other remote-sensing images are an essential part of fault investigations. In many cases, features of fault can be observed on aerial photographs that could not be readily identified during studies on the ground. Faults may appear as lineaments or an alignment of features resulting from various physical conditions created by faulting, such as disruptions of the normal ground surface along the lines of previous breaks, different soils on opposite sides, different rocks on opposite sides, different depths to water tables on opposite sides producing different vegetation, and displaced alluvium. For faults, the lines of the fault can be easily and immediately identified. At the other extreme, for some faults, the surface features seen on the aerial photographs may be so small and relatively insignificant that they can only be recognized as suspicious features by a geologist with considerable experience in fault studies and aerial photographic interpretations. There is a large element of experience and judgment in the interpretation of aerial photographs, and particularly in interpretation of recent fault activity.

Until the past few years, ordinary black-and-white photographs have been used. Much of the world has been photographed at scales generally of 1:30,000 to 1:60,000. These photographs are especially good for preliminary regional investigations and should be obtained wherever possible, because a large area is covered by a few photographs. For more detailed studies, scales of 1:12,000 to 1:20,000 are preferable. For stereo-

scopic viewing, which is absolutely necessary, 60% overlap and 30% sidelap are standard practice. Ability to interpret the photographs is dependent to some degree on the quality of the photography, but to a larger degree on the quality of the printing.

Ordinary aerial photographs are usually taken during midday. Starting in 1967, a research program was carried out jointly by the University of Nevada Department of Geology-Geography and Woodward-Lundgren & Associates, in which new photographic techniques were developed for the special purpose of studying active faults. A recent procedure of "low-sun-angle" aerial photography, utilizes photographs taken at different times of the day, and sometimes in different seasons of the year, depending on the fault trend and the azimuth of the sunlight (Cluff and Brogan, 1974). The purpose of the photography is to enhance shadows from subdued ground-surface irregularities. The optimum light condition is obtained when the sun is shining nearly perpendicular to the trend of the fault, in the direction from the uphill side of the fault scarplet toward the downhill side, at an angle slightly lower than the average slope of the scarplet (usually 10° to 25°). The most universally useful scale is about 1:12,000; with scales of 1:6,000 and 1:3,000 good for detailed analyses. While it is desirable to repeat the photography in both the early morning and late afternoon; experience has shown that photographs taken either in the early morning or late afternoon obtain most of the detail that can be obtained by flying at both times (Cluff and Brogan, 1974). Other types of images that are helpful include infrared and color images, photographs from satellites, and high-altitude aircraft photographs.

- The most useful type of photograph is the black-and-white, low-sun-angle, vertical aerial photograph.

- Color photographs are superior to black-and-white photographs taken at midday, but not to low-sun-angle aerial photographs. Where color photographs are not available, and where photographs must be taken for the purpose of a fault study, low-sun-angle, black-and-white photographs are recommended instead of color photographs taken at midday.

- The infrared photograph occasionally gives a better indication of differences in ground-water level or vegetation contrasts on the opposite sides of a fault, but low-sun-angle photographs appear to be better for evaluating fault activity.

- Satellite and high-altitude aircraft images can be useful for regional studies to identify structures that need careful evaluation with low-sun-angle photography or field studies.

Aerial photographs can generally be obtained from local aerial photographic companies, Agricultural Stabilization and Conservation Service, Soil Conservation Service, or U.S. Geological Survey.

5.4.1.4 Ground Reconnaissance - A ground reconnaissance is made to observe geological and geomorphic features which may be associated with faults and especially for any evidence of faulting as recent as Holocene. If a fault has been recently active, geomorphic evidence will be expressed at a few locations along its length. Therefore, more confidence in ground reconnaissance conclusions can be obtained by extending the reconnaissance beyond the site, examining known fault locations in the area for style of faulting and evidence of activity, field checking of lineations or suspicious features identified by aerial reconnaissance or interpretation of aerial

photographs, and describe any stratigraphic evidence which would demonstrate a lack of Holocene fault activity in the vicinity of the site.

5.4.1.5 Subsurface Exploration (Trenching) - The purpose of subsurface exploration is to demonstrate (1) the presence or absence of faults across the proposed facility, and (2) whether or not any faults crossing the facility site have had displacement in Holocene time or at some older time period. Subsurface exploration may consist of:

(a) Trenching and other extensive excavations to permit detailed and direct subsurface observations;

(b) Borings and test pits to permit collection of data at specific locations and depths; and

(c) Geophysical investigations of subsurface conditions.

Geophysical methods are indirect methods that require specific knowledge of subsurface conditions for reliable interpretations. Geophysical methods alone do not prove the absence of a fault nor the recency of activity.

Exploratory excavations provide the most positive and detailed method to establish the location and activity of faults on a given site. The exploratory excavation is commonly made by backhoe, a dozer, or some other means of exposing the subsurface materials. Selection of the excavation equipment depends upon accessibility, depth of excavation, difficulty of excavation, cost, length of the time excavation is to remain open, and the environmental impact of the excavation.

The purpose of the excavation is to expose the subsurface materials to a depth sufficient to enable individuals to make a

detailed inspection and evaluation of the excavation walls to determine if there are any fault features which will influence the feasibility of the project. In order to insure that the maximum information is obtained from each excavation, the following procedures are necessary:

(1) The excavation should be perpendicular to the trend of known faults, lineations, or suspicious features.

(2) The excavation must be as deep as possible, or at least 10 to 20 feet. This is necessary because fault features are better exposed in the deeper materials and because the deeper excavations often provide age relationships which are useful in establishing the activity of faults.

(3) The excavatin must be safe. The excavation must comply with local, state, or federal requirements for safety and permits. This may require that the excavation be shored, walls layed back, or the excavation be wider.

(4) The detailed inspection should be made by individuals experienced in logging fault features in test trenches. Since some of the significant fault features are difficult to recognize, experience is invaluable.

(5) Sufficient time should be allowed to inspect and log the excavation. Once the excavation is backfilled, the excavation log is the only evidence available. Therefore, it is very important that the log reflect the actual conditions observed in the excavation.

(6) The excavation, or a series of excavation, should extend a significant distance on either side of the fault and the proposed structure. Generally more than one excavation should be made across a fault or suspected fault. The number of trenches will depend on size of facility, tectonic environment, style of faulting, type of surface materials, and results of initial trench.

The logging of exploratory excavations and observation of "active" faults in test trenches is discussed by Taylor and Cluff (1973).

Exploratory trenches have been used with increased frequency for fault investigations. These trenches provide a better view of the nature of the fault than can be obtained from a study of the ground surface. The trenches allow examination of surface soils above a fault and can provide an opportunity to assess the relative active. The detailed logging of trenches must be done in a systematic manner by a geologist experienced in this type of investigation.

### 5.4.2 Conducting a Regional Study

The flow diagram for an appropriate geological study, Figure 9, shows the investigative methods and decision points that are to be used to demonstrate compliance or non-compliance. The purpose of the regional study is to start with a large area and continue to work towards smaller areas until the site and surrounding area is covered sufficiently to conclude that there is no evidence of a fault with Holocene displacement within 200 feet of the proposed site. Some of the significant considerations of the "Regional Study" on Figure 9 are as follows:

(1) Published evidence of Holocene faulting within 5 miles of a facility requires that additional steps be taken to establish if any of these faults project to within 3000 feet of a facility.

(2) If the published data does not indicate Holocene faulting within 5 miles of a facility, an aerial reconnaissance is required within a 5 mile radius of the facility because the published data could be inadequate or the data could be unavailable.

(3) Interpretation of aerial photographs is required for an area within 3000 feet of any proposed facility.

(4) A subsurface investigation (trenching) is reviewed at the facility if faults with evidence of Holocene displacement and/or lineations project to within 3000 feet of the proposed facility. The subsurface investigation is to include at least one (two or three would be more desirable) trenches excavated perpendicular to the fault or lineation trends and at least 200 feet beyond the active portion of the facility.

(5) In some cases, a subsurface investigation may be required to provide acceptable documentation even-though the previous steps have provided no evidence of Holocene faults at the proposed.

5.4.3 Conducting a Site Specific Study

The flow diagram for a site specific study is shown on Figure 9. The site specific study provides an alternative to the regional study and would generally be used if (1) there is considerable data available on the location and activity of

faults near the site, or (2) the age of surface materials at the site provide an opportunity to conclusively demonstrate that the site (and a 200 foot radius) is underlain by unfaulted materials older than Holocene. Some of the significant considerations of the "Site Specific Study" on Figure 9 are as follows:

(1) If on the basis of published data and/or a geological reconnaissance acceptable documentation can be provided that no Holocene faults are located within 200 feet of an active portion of the facility; the facility is in compliance. This may be possible for areas that are well studied or existing geological exposures are sufficient to demonstrate compliance.

(2) If on the basis of a subsurface investigation acceptable documentation can be provided that no Holocene faults are located within 200 feet of an active portion of the facility; the facility is in compliance. If Holocene fault planes are located within 200 feet, facility is in non-compliance and must relocate proposed active portion of facility.

(3) If the documentation is not acceptable to the Regional Director the regional study approach is required.

5.4.4 Basis for Distances Used in Appropriate Geological Study

The appropriate geological study (regional study and site specific study) shown on Figure 9 uses distances of 5 miles - for review of data and aerial reconnaissance, 3000 feet - faults or lineations within this distance require subsurface exploration, and 200 feet - no active portion of facility within this distance of Holocene fault. The basis for the distances are described below.

5.4.4.1 Basis of 5 Miles - Regional and aerial reconnaissance within 5 miles of the site is based on procedures required by NRC and Liquefied Natural Gas Facilities Safety Standards by the State of California Public Utilities Commission.

5.4.4.2 Basis of 3000 Feet - Evidence of faulting within or projecting within 3000 feet of a structure is a sufficient concern to require site specific studies because Bonilla (1967) has indicated that the distance from the centerline of the main zone of surface faulting to the outer edge of that zone is on the order of 3000 feet. Therefore, more detailed observations are required in this distance and any evidence of fault traces with Holocene displacement in this distance requires site specific studies.

5.4.4.3 Basis for 200 Feet - During historical surface faulting the actual fault displacement and associated deformation of the ground surface occurs in a narrow band adjacent to the surface fault trace. The width of the band depends on type of fault displacement (strike-slip, normal, or reverse-thrusting), amount of fault displacement, and site-specific characteristics of the near surface materials (rock, soil, clay, etc.). Normal and reverse faults generally produce wider zones of faulting and deformation than do strike-slip faults and the zone is generally wider in soils than in rock.

Much of the information on deformation of the ground surface adjacent to surface faulting comes from observations along the San Andreas fault after the 1906 earthquake. That fault and up to 20 feet of strike-slip displacement and the evidence shows that the half wide (on one side of the fault) of the deformation may be as little as 50 feet and as much as 700 feet. Of the 15 reliable observations 66% had a half width less than 200 feet and 80% had a half width less than 300 feet.

Examination of cases of historical faulting and exploration trenches excavated across fault traces with Holocene displacement has generally indicated that the majority of faults associated with historical and Holocene faulting have occurred within a band with a half width of 200 to 300 feet. Thus, this would represent the half width of the expected zone of faulting and deformation from the centerline of the surface faulting. Since, the intent of the standard is to locate the active portion of a waste management 200 feet from the closest fault (not the centerline of faulting) and since this distance is to include unfaulted materials it is considered a reasonable set-back distance from faults with Holocene displacement.

5.4.5 Reporting

The results of an appropriate geologic study should be presented in a report signed by a qualified geologist and the contents should be acceptable to another qualified geologist experienced in identifying and evaluating faults. Contents of the reports should include, but not be limited to, the following:

(1) Location of study area

(2) Key personnel conducting study

(3) Sources of available data

(4) Description of geologic setting and site conditions

(5) Investigative methods and approaches

(6) Aerial photographs or remote sensing images interpreted (type, scale, source, index number)

(7) Logs of subsurface exploration (showing details not diagrammatic)

(8) Geologic site map with exploration locations (1" = 200 feet, example)

(9) Regional geology map (1" = 2000 feet, example)

(10) Results, conclusions, and basis of findings

(11) Referenced cited

(12) Signed by Qualified Geologist.

In order to demonstrate that no Holocene fault occurs within 200 feet of the facility, it will be necessary to demonstrate that (1) there are no faults within 200 feet of the site, or (2) faults which are present are older than Holocene. It is likely that most sites for hazardous waste management facilities can be demonstrated acceptable. However, at some sites it may be difficult, if not impossible, to demonstrate that the faults are older than Holocene. In some cases it may not be possible to demonstrate that no Holocene faults cross a site because faults are present on the site but not covered by any Holocene or older deposits. Yet, regional studies, indirect evidence and professional judgment clearly supports conclusion of no Holocene displacement on the site. The regulatory process should be capable of resolving this lack of documentation when the indirect data and judgments indicate that the potential hazard and consequence are acceptable, have been adequately mitigated, or have been adequately considered in design. This is especially true if the proposed site is the only acceptable site on other more critical considerations.

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## APPENDIX A - GENERAL DISCUSSION OF EARTHQUAKES AND FAULTING

### GENERAL STATEMENT

The following discussion is given primarily for persons not familiar with faults and earthquake related problems. Individuals are encouraged to read and study this discussion to ensure a common understanding.

### CAUSES OF EARTHQUAKES

It cannot be claimed that there is only one cause of all earthquakes. A minor cause of earthquakes is volcanic activity. Some deeper earthquakes may perhaps be related to sudden changes in rock properties due to motion deep within the Earth's mantle. However, most destructive, shallow-focus earthquakes appear to be associated with a sudden rupturing (faulting) of the Earth's crust. The crust is a rock layer of varying thickness, ranging from 30 miles under continents to 3 miles under oceans, which is found world-wide and is composed of mainly basaltic and granitic rocks. The resulting earthquakes are caused by the sudden release of accumulative strain energy. The rupture, or break, is called a fault and is generally accompanied by displacement of blocks either vertically or horizontally or both, on opposite sides of the fracture.

This mechanical explanation of the creation of strong ground shaking, or an earthquake, only became widely accepted after the 1906 California earthquake. It is based on the "elastic rebound theory" of Professor H. F. Reid. Before Reid's time a common explanation was in terms of explosion-like phenomena at depth, often associated with the movement of hot magma (molten rock). In the 1906 earthquake, large-scale and continuous fault rupture was evident in the field. Of great importance,

geodetic surveys of the region existed before and after the earthquake. The U.S. Coast and Geodetic Survey had made triangulation measurements across the San Francisco Bay region in 1851-65, 1874-92, and 1906-07. Reid interpreted these surveys as showing between the first and third surveys (a) little changes in elevation, (b) significant horizontal right-lateral displacements of the crust parallel to the San Andreas fault, and (c) relative displacement of distant points on opposite sides of the fault of about 11 feet.

Reid stated, "It is impossible for rock to rupture without first being subjected to elastic strains greater than it can endure. We conclude that the crust in many parts of the Earth is being slowly displaced and the difference between displacements in neighboring regions sets up elastic strains, which may become larger than the rock rebounds under its own elastic stresses, until the strain is largely or wholly relieved. In the majority of cases, the elastic rebounds on opposite sides of the fault are in opposite directions."

The seismic waves which are generated when the fault ruptures arise from the movement of the rocks in the vicinity of the fault.

## SIZE OF EARTHQUAKES

Two measures of earthquake size have been found to be useful, intensity and magnitude. Unfortunately, these terms are often confused and sometimes even used synonymously. Magnitude attaches a single number to an earthquake which is independent of the distance from the earthquake center and independent of geological and soil conditions. For a measure of the variation of ground motion from point to point, an intensity scale is used. The intensity value is assigned by an experienced observer using a descriptive scale. Both measures are too

simple of describe the full complexity of an earthquake and should be used judiciously.

## Intensity Scales

Intensity is a rating of the severity of the ground motion at a specific location. The scale of measurement is based upon the sensations of persons, the behavior of natural objects, and upon physical damage to natural and man-made objects. Intensity scales came into being long before magnitude scales because intensity does not require instrumental observation. Over the years, different intensity scales have been devised. The scale must reflect the type of structure which is common to a particular region. The most widely accepted intensity scale in the United States is the Modified Mercalli Intensity Scale. It goes from I to XII on a twelve-point scale.

Intensity ratings are bound to be subjective, as reported intensities may take on several meanings, depending on who reports them and the type of construction in an area. The reported intensity may be the maximum intensity at the built-up area nearest the epicenter, or it may be what that intensity should have been, at the epicenter based on observations at a center of population some distance away. Many circumstances arise making it difficult to assign intensities. The lack of precision in the intensity index should be recognized. Basically, intensity refers to the measure of earthquake effects of all types at a specified place. It is not based on the true measurement, but it is rating assigned by an experienced observer using a descriptive scale.

Because intensity is defined by the observed effects on the Earth's surface, such as landslides or underground pipes broken, the intensity of an earthquake on a mid-oceanic ridge might be taken as zero. On the other hand, a smaller shock

centered near weak man-made structures on poor ground might yield a high intensity. For a given earthquake, intensity differs between localities depending upon the distance from the source, the severity of the shaking, the duration of shaking, the geologic foundation and the quality of design and construction.

## Magnitude Scales

Magnitude is based on ground motion as recorded by distant seismographs. The most commonly used method of calculating magnitude in the United States for moderate to large earthquakes is that of C. F. Richter. Other magnitude scales are, however, widely used by seismologists, both in the United States and in other countries, sometimes leading to what appears to be conflicting magnitudes. To briefly illustrate the technique used to calculate a magnitude for an earthquake consider the following case. A particular kind of seismograph (called a Wood-Anderson instrument) at a distance of about 62 miles (100 kilometers) from the epicenter records the earthquake ground motion. The recording is called a seismogram. A ruler with a centimeter scale is taken and the half-width ("amplitude") of the largest wave is measured and converted to microns ($10^4$ microns = 1 cm). The logarithm (to base 10) of this number is the Richter magnitude of the earthquake. For example, if the maximum amplitude measured is 1 cm, the Richter magnitude is 4.0. Empirical tables provide the necessary adjustment when the seismograph is at various epicentral distances, when other types of seismographs are used, for various focal depths, and for various types of waves.

# EARTHQUAKE ASSOCIATED DAMAGE

It is commonly held misconception that distance from the surface trace of an active fault is the best assurance against

earthquake damage. Experience has shown that the intensity of an earthquake is not necessarily highest at the surface trace of the earthquake-generating fault. If the structure is not astride an active fault, it matters little whether it is alongside the fault trace or several miles away, because energy reaching the surface will be almost the same at the two points, everything else being equal.

Earthquake damage depends on many variables: earthquake magnitude, epicentral location, depth of focus, duration of shaking, intensity of shaking, near-surface soil and geologic conditions, structural type, and design. Damage related to ground (or soil) conditions depends upon subsurface properties such as material density, shear strength, thickness, and water level. Thus, proximity to an active fault should not be given undue weight when deciding where to build; more consideration should be given to ground conditions and structural design.

Earthquake associated damage is usually manifest in three separate forms: (1) fault displacement; (2) strong ground motion (shaking); and (3) ground (or soil) failure.

## FAULTING

Faulting, as the movement or fracturing along faults is called, may have horizontal and vertical components of displacement and may vary from a fraction of an inch to many feet. In the California earthquake of April 18, 1906, horizontal offsets along the San Andreas fault averaged from 8 to 15 feet and extended from just north of San Juan Batista to north of Point Arena, a distance of more than 200 miles.

Fracturing and shearing associated with faulting is often observed in the field to be of a multiple and en echelon character, with several planes of displacement being formed

through geologic time (millions of years); thus the term fault zone is a more realistic designation. The exact location and characteristics of a fault zone are of vital concern in estimating the hazard from faulting. Once a fault is formed, it constitutes a plane of weakness that localize further adjustments.

Some fault zones, such as the San Andreas fault, are more than a mile wide in places, containing many "fault traces" within the broad zone. One might ask, "What is the relative risk of developing or locating structures within such wide active fault zone?" It depends upon factors such as type of development, intended land use, type of structure, and site location with respect to the active fault traces. The broad fault zones have been formed over long periods of geologic time and in some future geologic time (millions of years) not only may the present fault traces be reactivated, but new traces may be formed. However, if we consider this problem from the standpoint of "engineering design time," (of the order of 100 years say) the probability of fault movement is much higher along the most recent fault traces that lie within the broad fault zone.

It is often believed that assurance against earthquake damage is directly proportional to the distance from the surface trace of a known active fault or fault zone. There is much evidence that the intensity of an earthquake is not necessarily highest at the surface trace of the earthquake-generating fault. If the structure is not astride an active fault trace, so that displacement may shear it in two, it may not be decisive as a damage factor whether it is alongside the fault trace or several miles away; wave energy reaching the two sites may be comparable. Damage resulting from faulting occurs only where works of man are located astride the fault traces that move or within the zone of ground deformation adjacent to the fault trace.

## Types of Surface Faulting

Surface faulting can generally be divided into three types (Bonilla, 1967); main fault, branch fault, and secondary fault as shown on Figure 4. The main fault is actually a band of varying width which includes; closely spaced faults that are the location of the major surface displacement, and associated faults which decrease rapidly in number and amount of displacement away from the location of major fault displacement. The main fault trace is the surface fault with the greatest displacement, length, and continuity. The main fault trace generally receives the greatest consideration because the amount of fault displacement and the width of the band of faulting is greater than the other two categories of faulting.

A branch fault generally starts as part of the main fault but laterally along the fault it diverges from and extends well beyond the main zone of faulting. The branch fault generally shows the same type of displacement as the main fault and either joins it at the surface or is inferred to join in to the subsurface. While branch faults may form during some surface faulting and may be found associated with the main fault at several locations along its length, they do not exist along a major length of the fault nor do they result in a continuous zone of faulting from the main fault trace out to the branch fault trace.

Secondary faults are completely separated spatially from the main fault trace and from the branch fault trace. Secondary faults occur infrequently and generall involve a very small percentage of the total fault length.

When considering the potential for future surface faulting, it is important to remember that a continuous band of faulting is

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Secondary faults are completely separated spatially from the main fault trace and from the branch fault trace. Secondary faults occur infrequently and generally involve a very small percentage of the total fault length.

When considering the potential for future surface faulting, it is important to remember that a continuous band of faulting is

likely along the main fault trace; branch faults may occur adjacent to the main faulting but only along a small percentage (say 20%) of the total fault length and the width of faulting is generally smaller; and secondary faulting is a fairly rare event along a very small percentage of the total fault length (say 5%) and the amount and width of faulting is generally much smaller. It is important to realize that even in those cases where the surface faulting consist of a main fault, a branch fault, and secondary fault this does not represent a continuous zone of faulting, but a zone in which the three types of faulting occur as restricted bands of varying width with considerable unfaulted material inbetween the bands as shown on Figure 4. The important consideration is not the distinction between the types of faulting (main fault, branch fault, or secondary fault) nor the width in which these categories of faulting may occur, but the actual width of the fault zone adjacent to a proposed structure and more specifically the distance between the structure and any significant fault.

Width of Surface Faulting and Deformation

Surface fault rupture along a fault trace may be accompanied by displacement along the individual faults and by horizontal or vertical deformation (distortion or warping) of the ground surface extending for some distance on either side of the fault trace. The occurrence of deformation and the amount depends upon the type of faulting, the amount of fault displacement, and the properties of materials at specific sites along a fault trace (strength, type, and depth of materials).

Bonilla (1970) on the basis on statistical analysis of historical surface earthquakes reports that at least half of the historical faulting events in North America include subsidiary faulting. If one where to take the historical faulting data presented by Bonilla (1970) at its face value, it

could be inferred that the main zone of faulting could be up to 917 meters (3,000 feet) wide, the zone of branch faulting could be up to 4.8 kilometers (3 miles) wide, and the zone of secondary faulting could be up to 14.5 (9 miles) wide; all measured from the center line of the faulting. However, this data refers to the composite zone in which these different categories of faulting occur within narrow bands and not to a continuous zone of faulting along the entire length of the surface faulting. Such an interpretation of this data gives an erroneous and overly pessimistic view of the potential width of surface faulting and therefore the impact upon adjacent structures. Based on a review of historical earthquakes and reported surface faulting, reconnaissance and interpretation of aerial photographs along faults which have had Recent displacement, and review and examination of test trenches excavated across faults which have had Recent displacement. It is concluded that the width of faulting and associated ground deformation generally ranges from several feet to as much as several hundred feet (Taylor and Cluff, 1977).

Taylor and Cluff (1978) reviewed fourteen cases of documented deformation associated with the 1906 faulting along the strike-slip San Andreas fault near San Francisco, California. From that data it was concluded that the width of the faulting and deformation ranges from 3 meters (10 feet) to 211 meters (690 feet) with; 3 cases (21%) having a width greater than 61 meters (200 feet), 3 cases (21%) having a width between 30.5 and 61 meters (100 to 200 feet), and 8 cases (58%) with a width less than 30.5 (100 feet). It was also concluded that at distances greater than about 61 meters (200 feet) the deformation is generally insignificant. It is very important to emphasize that the deformations were associated with a fault that had displacements ranging from 12 to 20 feet horizontally, and the width of faulting and deformation would be less for surface faulting events with displacements of lesser amounts.

A recent study at two sites along the Wasatch fault (a normal fault with vertical displacement) by Swan, Schwartz, and Cluff (1980) reports that: (1) the fault has had accumulative vertical displacement on the order of 10 to 13.5 meters (33 to 44 feet) during about the last 12,000 to 13,000 years (Holocene), (2) the width of faulting is about 68 meters (222 feet), and (3) the width of deformation being about 120 meters (392 feet) or about 52 meters (170 feet) beyond the limits of faulting. Another recent study conducted by Woodward-Clyde Consultants (1980) along a thrust fault on the Brazil property identified a zone of faulting at least 120 meters (392 feet) wide. This faulting is believed to have occurred within the last 100,000 years.

Based on exploratory excavations across Holocene (active) faults the following general comments are made by Taylor and Cluff (1977):

- "Surface faulting is generally confined to narrow fault-traces in a wider zone of disturbance. The width of the fault-traces can range from a few feet to several tens of feet and is dependent on the type of faulting, amount of faulting, and geometry of the fault plane. Many times the major surface faulting and fault displacement occur along a single fault-trace which is referred to as the main fault-trace."

- "The zone of disturbance can have a width of from a few feet up to 50 feet or more and frequently has a width of several hundred feet. This zone of disturbance includes the individual fault-traces (or main fault-trace) and auxilliary or secondary cracks branching

obliquely from or lying subparallel to the fault-traces."

- o "Surface deformation and distortion of structures is frequently reported within a zone several tens to several hundred feet wide adjacent to the surface faulting, and within the zone of disturbance."

- o "The geologic and historic record of fault activity demonstrates that the location of future surface faulting will most likely occur on or near the most recently active fault-trace."

- o "For an engineering project or structure located across or in the vicinity of a fault, the primary consideration is the possibility of recurrent movement on that fault within a time period which is considered significant to that project or structure."

A review of the above data will show that while the width of surface faulting and deformation may in some cases be several thousand feet wide, it generally ranges from a few feet to several hundred feet. However, the major consideration should not be the width of the zone of faulting but the distance from the fault having displacement.

Strong Ground Motion (Shaking)

Damage from strong ground motion (shaking) is caused by the transmission of earthquake vibrations from the ground into the structure. The main variable factors that determine the extent of vibrational damage are: type of ground, earthquake-

resistant design, quality of materials and construction, and intensity and duration of shaking. During moderate to large earthquakes, it is the strong shaking that usually inflicts the most damage to man-made structures.

Damage from Ground Failure

Damage from ground failure may occur in several different forms; landsliding, liquefaction, lurching, settlement, and seismically induced flooding.

It is common for earthquake-triggered landslides to occur as renewed movements of old landslide deposits. Area subject to slope instability could be subject to earthquake-triggered landslides.

Liquefaction occurs when granular, essentially cohesionless soils undergo loss of shear strength due to the buildup of fluid pressures in the soil pore water (caused by cyclic loading during earthquakes). When the loss in strength is low to moderate, partial liquefaction may cause ground settlement and associated ground cracking. However, when liquefaction is complete, the soil can behave as a fluid, and catastrophic failures, including soil flows and landslides, have occurred as a result. Partial liquefaction during strong ground shaking may occur in dense to very dense cohesionless soils; complete liquefaction typically occurs only in loose to medium dense cohesionless soils.

Seismic settlement is also typically associated with cohesionless soil deposits but can also occur in poorly placed or uncompacted man-made fill. The strong ground shaking that occurs during earthquakes will densify loose granular soils. When these soils are above the groundwater table, their densification and resulting ground subsidence will occur

rapidly. When located below the groundwater table, the pore water pressures that have developed during the shaking must begin to dissipate before a decrease in soil volume can occur and, as a result, settlement occurs at a rate commensurate with the flow of water from the cohesionless soil layer.

Lurching may be generally defined as the development of all types and sizes of irregular ground fractures, cracks, and fissures associated with shaking, settling and the passage of surface waves during earthquakes. In this general sense, ground cracks that occur as a result of liquefaction, compaction, settlement, or landsliding may be termed lurch cracks. More specifically, lurching involves the seismically induced lateral movement and spreading of ground toward a "free face," together with the development of associated tension cracks in the ground behind the free face.

## APPENDIX B - FAULTING AND GEOMORPHIC FEATURES OF FAULT ZONES

The three main types of faults considered within this discussion are strike-slip, normal-slip, and reverse-slip faults. Each of these three types of faults is characterized by a distinctive type of movement and geometry. Below is a discussion of these fault types:

Strike-Slip Fault - A strike-slip fault (Figure 3) is one in which displacements are essentially parallel to the strike of the fault, the movement primarily in a horizontal direction with little vertical displacement. The fault planes on strike-slip faults are most often nearly vertical. Strike-slip faults are of two types: right-lateral and left-lateral. In a right-lateral fault the displacement is such that, in plan view, the side opposite the observer appears displaced to the right. In a left-lateral fault this displacement appears to the left. Strike-slip faults are common in an environment subject to compression of blocks or plates. Depending on their orientations, structures across or in the vicinity of a strike-slip fault can be subject to compression, extension, displacement, or distortion.

Normal-Slip Faults - A normal-slip fault (Figure 3) is one in which the one side has apparently moved downward relative to the other side. The movements may involve vertical components only, or combinations of vertical and horizontal displacements. The angle of the fault plane in normal-slip faults is generally 45°-90°, and these types of faults generally form in a tensional environment characterized by a lengthening of the earth's crust. The zone of faulting is more pronounced and wider on the down thrown (lower) side eventhough the fault displacement and slope instability appears more dramatic on the upper side above the steep fault scarp.

Reverse-Slip Faults - A reverse-slip fault (Figure 3) is one in which the upper block appears to have moved upward relative to the lower block. As in normal-slip faults the movement of reverse-slip faults may involve vertical components only or a combination of both vertical and horizontal displacements. The fault plane of reverse-slip faults dip at angles of 45° and less, and generally form in a compressionable environment characterized by a shortening of the crust.

Of primary importance in the identification, characterization of length and type of movement, and assessment of future rupture patterns in active fault zones is the study of fault related geomorphic features expressed at the earth's surface (Slemmons, 1977). Each of the three fault types discussed above exhibit characteristic geomorphic features, with strike-slip faults exhibiting the simplest features and reverse-slip faults exhibiting the most complex. The morphology varies from small scale features to large scale geomorphic features that form the main topographic expression of the faulting. Following is a brief discussion of the main geomorphic features associated with each of the three fault types.

Landforms associated with strike-slip faults reflect the primarily lateral sliding of opposing blocks past one another, with splays and branch faults and en enchelon configurations common and characterizing the fault zone as an area of multiple blocks with complex lateral sliding relations. As opposing blocks slide laterally, some blocks are relatively depressed to form sags or sag ponds, or elongated graben may form between parallel breaks. Other slivers are raised, tilted, or slid diagonally to produce knolls and shutter ridges; elongated horsts may be uplifted between traces. Notches and trenches or troughs along the fault may reflect increased erosion of the crushed or broken rocks, or they may be primary features. The most prominent indicator of vertical movements and probably the

most useful in terms of recency of movement is the presence of and freshness of scarps, which are often very long in extent, while horizontal shifts are probably best displayed by offsetting of drainage channels and drainage related features. Typically, features associated with strike-slip faults are in alignment with one another and define lineaments best observed from the air or in aerial photographs.

Surface expression of faulting associated with normal-slip faults is generally more complex than for strike-slip faults. In general, normal-slip faults have a large component of vertical displacement, and develop steep, high scarps. Branch faults are common and tend to transfer displacement to more than one fault, and in addition, the inclined nature of many of the fault planes provide the possibility of faulting and secondary failures in surficial materials. Subsidiary faulting or disturbances are often restricted to the downthrown block. Slemmons (1977) describes the following five features characteristic of normal faults:

Simple Fault Scarps - Surface rupturing along a single break which extends to the earth's surface. The scarp in this type of break represents the main fault plane.

Fault Fissure Scarps or Fissure Trace - Formation of a near vertical fissure at some distance back from the tip of the downthrown block, this fissure brancking off the main fault plane. This type of break is most often formed in unconsolidated alluvial materials and the unstable nature of the unconsolidated surficial materials generally results in slumping into the fissure.

Trench Trace Scarps or Graben Fault-Trace Scarps - These scarps result from the gravitational failure of slump blocks into the fault fissure described above. The slumps may occur on either side of the fault fissure.

Longitudinal or Step Trace Scarps - These scarps result from one or more slump blocks on the uphill side of the fault fissures, resulting in a staircase arrangement.

Subsidence Trace Faults or Scarps - This type of scarp normally forms where the fault fissure is filled by semi-plastic flow of materials instead of by slumping.

The geomorphic features of reverse-slip faults are generally more subtle and not as easily distinguised as strike-slip and normal-slip faults. In general, the lower dip angles of the fault plane results in less conspicuous, more irregular fault traces and scarps of complex patterns. Often numerous branch faults cut to the surface from the main fault, resulting in complexly shattered surface displacements. The fault relations are further complicated and obscured due to the formation of large landslides and gravity slips in the upper block (Figure 3) as a result of the overthrusting. The lower block, in contrast, undergoes little distortion.

## APPENDIX C - HOLOCENE DEPOSITS AND ACTIVE FAULTING

The Holocene is generally defined as an epoch of the Quaternary period extending from approximately 11,000 years ago to the present time. Holocene deposits are those formed within this time period, during which climatic and sea level conditions, and geomorphic processes have been similar to or are ongoing with those now prevailing. Holocene deposits primarily form in depositional environments, in such places as flood plains, alluvial fans, coastal terraces, deltas in estuaries reservoir or bays, and mudflats or marshland. Holocene deposits can also form in relatively temporary depositional environments, such as in stream channels or on an adjacent beaches, as well as in erosional movement areas characterized by landsliding and landslide deposits.

Depending on such conditions as the physiographic and climatologic setting, the type and degree of weathering process, the relative rates of erosion and deposition, and other factors, different areas of the U.S. are characterized by relatively higher or lower amounts of Holocene deposit formation. In areas where Holocene deposits are extensive, observation of physiographic features to identify faults and to assess the recency and types of movements is generally adequate. In areas where Holocene deposits are scanty or formed in very localized areas, fault related features must be identified using older Quaternary or Pre-Quaternary deposits.

The presence of faulting can be established through physiographic features or stratigraphic and structure relationships within the Quaternary or older deposits. However, the recency of fault activity is more difficult to establish in older deposits. In this case, ongoing or Holocene processes superimposed upon the Quaternary and older deposits must be identified and evaluated in terms of fault related

discontinuities. Holocene soils are characterized by lack of soil development or weathering. In areas where layering is not obvious, age dating of materials at various depths can be carried out to establish time horizons. Discontinuities across faults which truncate or delete soils, weathering layers, or time horizons can be used to establish recency of activity. Where deposits or landforms of known Holocene age are offset or displaced by faults, movement along the fault is established to have occurred within the last 11,000 years. As major geologic processes such as faulting are long lived, lasting millions or tens of millions of years, movement along faults within the past 11,000 years can reasonably be considered as evidence for activity and a high potential for future activity along a fault.

Physiographic features which are commonly associated with fault activity include scarps, trenches or troughs, notches, parallel ridges, offset drainage channels, saddles, sag ponds, ponded alluvium, closed depressions, and shutter ridges, these features often in alignment with one-another. Fault related features of this sort are primarily temporary and ephemeral in a geologic sense, and are subject to modification and obliteration by ongoing geomorphic processes. The features tend to be best preserved in arid regions, while relatively quick obliteration of the features can occur in humid regions or in areas subject to modifications by activities of man.

While many areas of the United States have Holocene deposits and landforms of significant extent such that evaluation of fault presence and activity can be achieved, there are areas where Holocene deposits and landforms are not well developed. These are in areas where glacial activity has stripped the surficial ground cover and left highly resistant bedrock such that inspection of Holocene deposits or landforms for fault related features in hindered, and the presence of potentially

TABLE 1
AREAS OF THE UNITED STATES
REQUIRING COMPLIANCE WITH THE STANDARD

ALABAMA
- none

ALASKA
- Election Districts
  - Fairbanks-Fort Yukon
  - Wade Hampton
  - Yukon-Kuskokwim
  - Bethel
  - Bristol Bay
  - Aleutian Islands
  - Kodiak
  - Kenai-Cook Inlet
  - Seward
  - Anchorage
  - Palmer-Wasilla-Talkeena
  - Cordova-Valdez
  - Lynn Canal-Icy Straits
  - Juneau
  - Sitka
  - Wrangell Petersburg
  - Ketchikan-Prince of Wales

ARIZONA
- Cochise
- Graham
- Greene
- Yuma

ARKANSAS
- Fulton
- Randolph
- Clay
- Polk
- Izard
- Stone
- Cleburne
- Sharp
- Independence
- White
- Prairie
- Lonoke
- Arkansas
- Lawrence
- Jackson
- Woodruff
- Monroe
- Greene
- Craighead

ARKANSAS (continued)
- Poinsett
- Cross
- St. Francis
- Lee
- Monroe
- Phillips
- Mississippi
- Crittenden

CALIFORNIA
- all counties

COLORADO
- Saguache
- Hinsdale
- Mineral
- Rio Grande
- Archuleta
- Conejos

CONNECTICUT
- all counties

DELAWARE
- none

FLORIDA
- none

GEORGIA
- Warren
- Lincoln
- Columbia
- McDuffie
- Glascock
- Washington
- Johnson
- Richmond
- Jefferson
- Burke
- Emanuel
- Jenkins
- Candler
- Dade
- Catoosa
- Walker
- Chattooga
- Floyd

GEORGIA (continued)
- Whitfield
- Gordon
- Murray
- Bartow
- Fannin
- Gilman
- Pickens
- Cherokee
- Cobb
- Fulton
- Union
- Lumpkin
- Dawson
- Forthsyth
- Towns
- White
- Hall
- Gwinnett
- De Kalb
- Rabun
- Habersham
- Banks
- Jackson
- Barrow
- Walton
- Rockdale
- Newton
- Stephens
- Franklin
- Madison
- Clarke
- Oconee
- Hart
- Elbert
- Oglethorpe
- Greene
- Jasper
- Putnam
- Wilkes
- Taliaferro
- Hancock
- Treutlen
- Screven
- Bulloch
- Effingham
- Bryan
- Chatman

HAWAII
- Principal Islands
  - Hawaii
  - Maui
  - Honolulu

IDAHO
- Clark
- Fremont
- Jefferson
- Madison
- Teton
- Bonneville
- Bingham
- Power
- Cassia
- Caribou
- Bannock
- Oneida
- Franklin
- Bear Lake

ILLINOIS
- Union
- Alexander
- Pulaski
- Monroe
- Randolph
- St. Clair
- Clinton
- Washington
- Perry
- Jackson
- Marion
- Jefferson
- Franklin
- Williamson
- Johnson
- Massac
- Wayne
- Hamilton
- Saline
- Pope
- Hardin
- Gallatin
- Jersey
- Macoupin
- Madison
- Montgomery
- Bond
- Christian
- Moultrie
- Shelby
- Douglas
- Edgar
- Coles
- Cumberland
- Clark
- Crawford
- Jasper

ILLINOIS (continued)
- Effingham
- Clay
- Richland
- Edwards
- White
- Wabash
- Lawrence
- Fayette

INDIANA
- Sullivan
- Knox
- Gibson
- Posey
- Vanderburgh

IOWA
- Mills
- Fremont
- Page

KANSAS
- Washington
- Marshall
- Nemaha
- Brown
- Doniphan
- Atchison
- Riley
- Pottawatomie
- Jackson
- Jefferson
- Leavenworth
- Wyandotte
- Geary
- Wabaunsee
- Morris
- Lyon
- Osage
- Shawnee
- Douglas
- Johnson
- Franklin
- Anderson
- Linn
- Miami
- Henderson
- Union
- Webster
- Critenden
- Caldwell
- Lyon
- Trigg

KANSAS (continued)
- Calloway
- Bell
- Harlan
- Letcher
- Livingston
- McCracken
- Marshall
- Graves
- Ballard
- Carlisle
- Hickman
- Fulton

LOUISIANA
- none

MAINE
- all counties

MARYLAND
- none

MASSACHUSETTS
- all counties

MICHIGAN
- none

MINNESOTA
- none

MISSISSIPPI
- none

MISSOURI
- St. Charles
- St. Louis
- St. Louis City
- Franklin
- Jefferson
- Crawford
- Washington
- St. Francis
- Ste. Genevieve
- Perry
- Dent
- Texas
- Howell
- Shannon
- Oregon
- Iron
- Reynolds
- Carter

MISSOURI (continued)
- Madison
- Wayne
- Ripley
- Butler
- Bollinger
- Stoddard
- Cape Girardeau
- Scott
- Mississippi
- New Madrid
- Dunklin
- Pemiscot

MONTANA
- Flathead
- Sanders
- Lake
- Teton
- Missoula
- Lewis & Clark
- Powell
- Cascade
- Granite
- Deer Lodge
- Jefferson
- Meagher
- Broadwater
- Silver Bow
- Wheatland
- Beaverhead
- Madison
- Gallatin
- Park
- Sweet Grass
- Stillwater

NEBRASKA
- Sarpy
- Cass
- Lancaster
- Ofoe
- Gage
- Jefferson
- Johnson
- Paroner
- Nemaha
- Richardson

NEVADA
- all counties

NEW HAMSPHIRE
- all counties

NEW JERSEY
- all counties

NEW MEXICO
- Rio Arriba
- Taos
- Los Alamos
- Sandoval
- Santa Fe
- Bernalillo
- Valencia
- Torrance
- Catron
- Socorro
- Sierra
- Grant
- Hidalgo

NEW YORK
- Niagara
- Orleans
- Genesee
- Erie
- Wyoming
- St. Lawrence
- Franklin
- Clinton
- Jefferson
- Lewis
- Oneida
- Herkimer
- Hamilton
- Essex
- Warren
- Fulton
- Montgomery
- Otsego
- Washington
- Saratoga
- Schenectady
- Schoharie
- Delaware
- Albany
- Rensselaer
- Greene
- Columbia
- Ulster
- Sullivan
- Dutchess
- Orange
- Putnam
- Westchester
- Rockland

NORTH CAROLINA
- Cherokee
- Clay
- Graham
- Swain
- Macon
- Haywood
- Jackson
- Madison
- Buncombe
- Transylvania
- Yancey
- Henderson
- Mitchell
- McDowell
- Polk
- Avery
- Burke
- Rutherford
- Watauga
- Caldwell
- Ashe
- Alleghany
- Wilkes
- Surry
- Alexander
- Catawba
- Lincoln
- Iredell
- Rowan
- Cleveland
- Gaston
- Mecklenburg
- Cabarrus
- Stanly
- Union
- Anson
- Richmond

NORTH DAKOTA
- none

OHIO
- none

OKLAHOMA
- Tulsa
- Creek
- Lincoln
- Oklahoma
- Grady
- Stephens
- Cleveland
- McClain

OKLAHOMA (continued)
- Garvin
- Murray
- Carter
- Pottawatomie
- Okfuskee
- Seminole
- Pontotoc
- Johnston
- Marshall
- Hughes
- Coal
- Atoka
- Bryan
- Okmulgee
- Muskogee
- McIntosh
- Haskell
- Le Flore
- Pittsburg
- Latimer
- Pushmataha
- Choctaw
- McCurtain

OREGON
- none

PENNSYLVANIA
- Susquehanna
- Wyoming
- Lackawanna
- Wayne
- Pike
- Luzerne
- Monroe
- Carbon
- Schuylkill
- Lebanon
- Lancaster
- Berks
- Chester
- Montgomery
- Bucks
- Lehigh
- North Ampton

RHODE ISLAND
- none

SOUTH CAROLINA
- all counties

SOUTH DAKOTA
none

TENNESSEE
Lake
Obion
Dyer
Lauderdale
Tipton
Shelby
Weakley
Gibson
Crockett
Haywood
Fayette
Henry
Carroll
Madison
Hardeman
Scott
Morgan
Cumberland
Bledsoe
Sequatchie
Johnson
Carter
Sullivan
Washington
Greene
Hawkins
Cocke
Hancock
Hamblen
Grainger
Sevier
Claiborne
Union
Knox
Blount
Monroe
Polk
Campbell
Anderson
Roane
Rhea
Meigs
Hamilton
Loudon
McMinn
Bradley

TEXAS
none

UTAH
Box Elder
Cache
Rich
Weber
Morgan
Davis
Salt Lake
Tooele
Summit
Wasatch
Utah
Juab
Millard
Sanpette
Sevier
Duchesne
Carbon
Emery
Piute
Beaver
Wayne
Iron
Garfield
Washington

VERMONT
all counties

VIRGINIA
Lee
Wise
Scott
Dickenson
Buchanan
Russell
Tazewell
Washington
Smyth
Bland
Wythe
Grayson
Giles
Pulaski
Carroll
Craig
Montgomery
Roanoke
Floyd

WASHINGTON
Watchcom
Skagit
Clallam

WASHINGTON (continued)
Jefferson
Snohomish
Okanogan
Chelan
King
Mason
Grays Harbor
Pacific
Lewis
Ferry
Douglas
Grant
Yakima
Skamania
Cowlitz
Clark
Wahkiakum
Thurston
Pierce
Kittitas

WEST VIRGINIA
McDowell
Mercer
Summers
Monroe

WISCONSIN
none

WYOMING
Park
Yellowstone National Park
Teton
Fremont
Sublette
Lincoln
Uinta

TERRITORIES OF THE UNITED STATES:

Guam
all

Puerto Rico
all

U.S. Virgin Islands
all

America Samoa
all

Commonwealth of the Northern Mariana
all